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THE SEA ICE COVER IN THE SEA OF OKHOTSK
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National Aeronautics and
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ABSTRACT

Sea ice conditions in the Sea of Okhotsk, as determined by satellite images from the Electrically Scanning Microwave Radiometer (ESMR) on board Nimbus 5, have been analyzed in conjunction with the known oceanography. In particular, the sea ice coverage has been compared with the bottom bathymetry and the surface currents, water temperatures, and salinity. It is found that ice forms first in cold, shallow, low-salinity waters. Once formed, the ice seems to drift in a direction approximating the Okhotsk-Kuril current system. Two basic patterns of ice edge positioning which persist for significant periods have been identified as a rectangular structure and a wedge structure. Each of these is strongly correlated with the bathymetry of the region and with the known current system, suggesting that convective depth and ocean currents play an important role in determining ice patterns.

PROCEEDINGS OF THE 1974 RCMC MEETING

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OCEANOGRAPHIC INFLUENCES ON THE SEA ICE COVER IN THE SEA OF OKHOTSK

I. INTRODUCTION

The Sea of Okhotsk is a relatively shallow body of water bounded by Sakhalin Island, Siberia, the Kamchatka Peninsula, and the Pacific Ocean (Figure 1). It is separated from the Pacific by the Kuril Island chain and the accompanying 2300 m deep sill; its only remaining outlets are through two narrow and very shallow straits to the west



Figure 1. The Okhotsk Sea Region.

and south of Sakhalin Island, leading to the Sea of Japan. The protected nature of the sea facilitates the formation of sea ice, so that the Sea of Okhotsk tends to form ice earlier and retain it later than other regions of equally poleward latitude. This protected nature combined with the limited area ($1,528,000 \text{ km}^2$) make the Sea of Okhotsk an interesting region in which to examine the relationship of an ice cover to its oceanographic surroundings.

Four major oceanographic factors influence sea ice formation: temperature, salinity, convective depth, and water motion. The effects of temperature are obvious, temperatures near to or below the freezing point being necessary for ice formation. Other factors being equal, a rise in salinity creates a decrease in the freezing temperature, thus delaying ice formation, but at the same time it creates an even more rapid decrease in the temperature of density maximum for the given mass of water. For water with a salinity below 24.7 ‰ the temperature of the freezing point is less than the temperature of density maximum, while for water with a salinity above 24.7 ‰ the temperature of the freezing point is greater than that of density maximum. Thus when a uniform water column with a salinity greater than 24.7 ‰ is cooled by the atmosphere, the cooling surface water convects down, for its lowered surface temperature yields densities greater than those of the waters beneath. As a consequence, if the salinity exceeds 24.7 ‰, the entire depth of vertically uniform waters tends to be cooled to or near the freezing point before freezing can commence at the surface, and once freezing begins it will tend to proceed rapidly, as it will be unhindered

by warm water underneath (Donn, 1975). In waters with a stable density stratification, the cooling needs to occur only to the bottom of the mixed layer, if one exists. Thus the depth of greatest relevance is not the total water depth but the convective depth; however, these are often correlated, especially in shallow waters. The final supporting condition for ice formation is a certain dampening of motion, with excessive current-related or tidal motion slowing both the formation and concentration of ice.

With these four factors in mind, and a sketch of the physical characteristics of the Sea of Okhotsk (Section 2), a delineation of likely areas of ice formation and cover will be attempted. These areas are then compared with satellite imagery of the Okhotsk region.

The imagery used to determine ice conditions is from the Electrically Scanning Microwave Radiometer (ESMR) on board Nimbus 5. Microwave sensing can be used to detect sea ice due to the differing emissivities of water and ice. ESMR records brightness temperatures at a wavelength of 1.55 cm, a wavelength at which the emissivities of first year ice, multi-year ice, and open water are approximately 0.92, 0.84, and 0.40 respectively. This produces a sharp contrast in the brightness temperatures of ice and water, and since the ice in the Sea of Okhotsk is all first year ice, the additional ambiguity of the multi-year component is eliminated. Although other complications arise, such as those dealing with the stage of ice growth, surface temperature, melt ponds, snow cover, ridging, salinity, and variations in ice thickness, still it is felt valid that the brightness temperatures recorded by the satellite instrument reflect the sea ice concentrations in a roughly linear fashion, higher brightness

temperatures corresponding to more heavily concentrated ice. A fuller discussion of these considerations is presented in Zwally and Gloersen (1977). Spatial variations do occur within the ice, such as pockets of low and high salinity and localized pools of melted ice; however, it will be assumed that such effects are essentially random, producing a background noise which will be non-detrimental to the study. A certain amount of interference is generated by weather patterns (Wilheit, 1978); however, the time-averaged brightness temperature of sea water augmented by contributions from weather events remains below that of sea ice and hence is not a factor in the qualitative study presented here. Although the instrument resolution is low--approximately 30 km--compared to satellite images in the visible band, ESMR has the important advantages of providing frequent coverage and of having all-weather sensing capabilities (Zwally and Gloersen, 1977).

In general the ESMR images show a sharp transition from open water brightness temperatures of 130-145 K to ice-covered brightness temperatures of 193-250 K. Under undisturbed atmospheric and oceanographic conditions, the intermediate brightness temperatures reflect ice concentrations between 15% and 60%. However, temperatures of 140-165 K also occur frequently over ice-free waters due to various atmospheric events; and it is for these various reasons that the 193 K contour will be used to depict the ice configurations in most of the figures below (Figures 5-6 and 9-11). Calculations by Zwally and Gloersen (1977) indicate that this isotherm occurs at approximately 60% ice concentration.

II. PHYSICAL CHARACTERISTICS OF THE SEA OF OKHOTSK AND EXPECTED AREAS OF ICE FORMATION

The Sea of Okhotsk is stratified vertically by temperature and salinity, with the water density structure being unstable in winter. As water cools, convection takes place down to 1000-1300 m, where possible, providing a mixed layer which reaches the sea floor in most of the Sea (Leonov, 1960). There is significant horizontal variation in surface water properties due to the countering inflows of cold fresh waters from coastal runoff and warm saline waters from the Pacific Ocean. The Pacific waters enter through channels in the eastern Kuril chain, flow north along the Kamchatka Peninsula, and continue approximately parallel to the coastline, resulting in a cyclonic path from which they exit through the western Kurils (Figure 2). These waters become gradually cooler and less saline as they mix with fresh coastal runoff from the large number of streams and rivers along the entire coast. The salinities immediately bordering the coastline remain below 30 ‰ throughout the year. Enclosed coastal areas largely sheltered from the Pacific inflow tend to have even lower salinities and colder temperatures (Favorite *et al.*, 1976).

Surface temperatures in the sea vary by about $\pm 1^{\circ}\text{C}$, being warmer near the eastern Kuril Islands because of Pacific inflow. As these temperatures in wintertime are everywhere near or below 0°C , ice formation is, thermally, possible throughout the Sea, but most likely north of Sakhalin Island, the coldest region. Salinity also decreases with distance from the eastern Kurils, again due to the Pacific inflow. Except for the region of Pacific inflow, surface waters as a whole

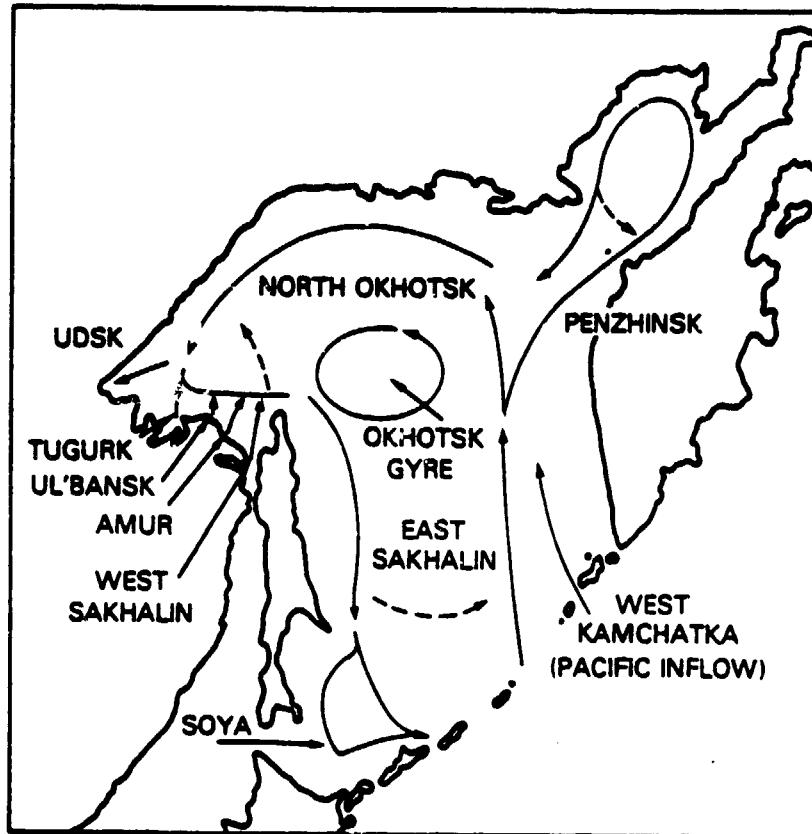


Figure 2. Currents of the Okhotsk Sea, schematized from a figure of Favorite et al. (1976).

are fairly dilute ($31 \text{ }^{\circ}/\text{o}$ - $32 \text{ }^{\circ}/\text{o}$), with the most dilute waters naturally being in those locales most heavily affected by coastal runoff. With regard to ice formation, salinity stresses favor the area north of Sakhalin Island, the Zaliv Shelikhova (especially the Penzhinskaya Guba), and near-coastal waters as a whole.

A third factor in ice formation is water motion. Excessive current or tidal motion slows both formation and concentration of ice, while the relative calmness of enclosed waters aids in the crystallization and

further growth of sea ice. As Leonov (1960) points out, water motion in an area as shallow as the Sea of Okhotsk depends highly on sea floor topography. Sloping or significant relief in the sea floor is thus a major cause of water motion and the spatial distribution of upwelling.

The final important consideration for ice formation is water depth. It has often been observed that ice, for a variety of reasons, typically forms in areas with an elevated sea floor, notably over continental shelves. In the Sea of Okhotsk, the sea floor is effectively the bottom of the convective layer; hence the depti. of water that needs to be cooled before freezing begins is determined by the bathymetry (Leonov, 1960). Figure 3 presents a map of the bathymetry of the region. The shallow shelf area is most extensive in the northern portion of the Sea, while there exist three relatively deep basins: the 1800 m Kuril Basin, the 400 m Tinro Basin, and the 800 m Derugin Basin.

On the basis of the above factors, one would expect that ice in the Sea of Okhotsk would form preferentially in cold, low-salinity, shallow, sheltered coastal areas at some distance from the Pacific inflow. Such areas include the Zaliv Shelikhova (especially the Penzhinskaya Guba), the Tauyskaya Guba, and the Sakhalinskiy Zaliv. The entire gulf area between the city of Okhotsk and Sakhalin Island is noted for very low temperatures and dilute waters, has a flat shallow sea floor, and is also somewhat sheltered from the Pacific inflow, thereby making this another region of expected ice formation. While there are many additional enclosed coastal areas likely to be covered by ice early in the season, these are too small to be verified by the available imagery.

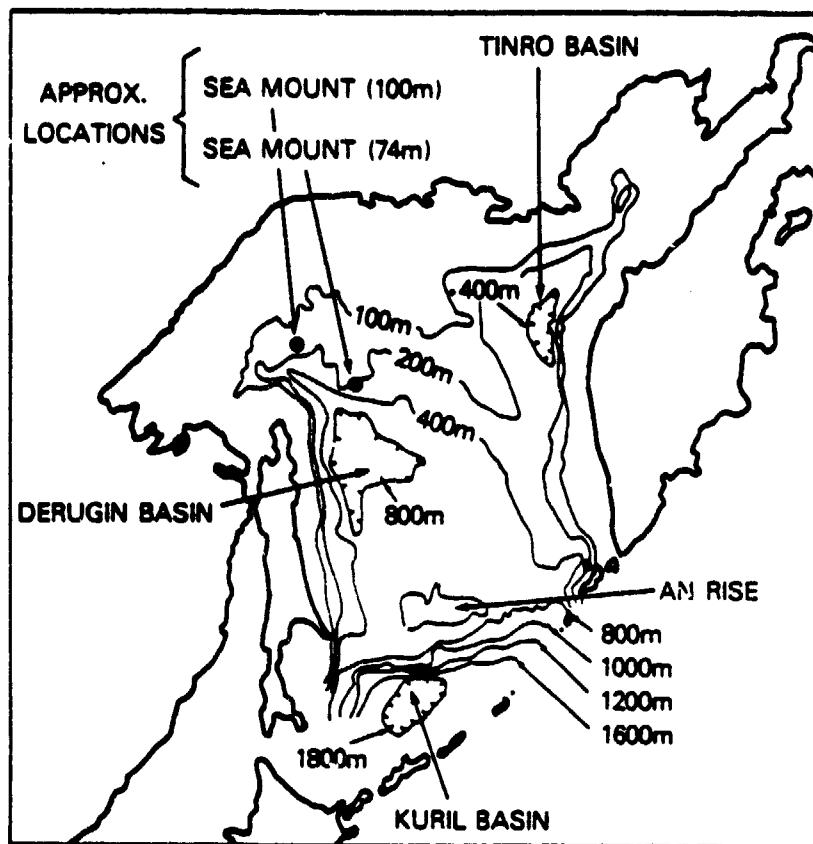


Figure 3. Bathymetry of the Okhotsk Sea, abbreviated from Chart #1 of Chase et al. (1970).

The expected areas are in fact the areas of first ice concentration (Figure 4). Ice forms primarily in the northwest gulf area, secondarily in the Penzhinskaya Guba, and tertiary in the Tauskaya Guba. This confirms that the factors enumerated above are indeed indicative of ice formation tendencies.

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Figure 4. Areas of early ice formation, as illustrated by the 19 December 1975 conditions. In this and the following diagrams, the heavy line is the continental boundary. The remaining lines in this figure and in Figures 7-8 locate the ice boundary as determined by the ESMR-5 153 K brightness temperature contour (approximately 15% ice concentration), while the remaining lines in Figures 5-6 and 9-11 locate the ice boundary as determined by the ESMR-5 193 K temperature contour (approximately 60% ice concentration).

III. CURRENTS AND SEA ICE DRIFT

The water circulation in the Sea of Okhotsk is dominated by the Okhotsk Gyre. The Sea is a system in which water cannot move inward, due to an outward Ekman component, and cannot move outward, due to the coastline. Evidence for sea ice drift along established current patterns is strong, with the ice moving cyclonically along the basic current system. Thus it appears that the forces affecting ice movement are essentially concurrent with those affecting water movement, yielding a large-scale

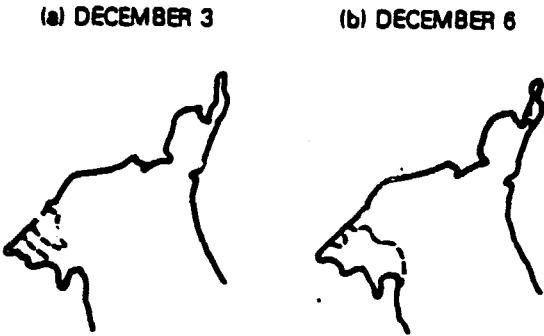


Figure 5. Ice pattern shift from 3 December 1974 to 6 December 1974.

ice drift which follows the persistent Okhotsk-Kuril current system. Although the ESMR imagery cannot reveal drift patterns directly, some indication of drift can be inferred by noting the changing positions of distinct ice formations, with the persistence of the formations suggesting that the apparent motion is not caused by lack of resolution or by atmospheric interference. Also, some indication can be inferred from the general spreading of the ice cover, as in Figures 5a-5b.

There is also evidence that, as the ice cover expands, the surface currents are at least somewhat contained by the ice boundary. Illustrative of this is the movement of the ice protrusion north of Sakhalin Island over the 18-day period 18 January-5 February 1973 (Figure 6). This formation travels upwards of 100 km along the ice boundary.

MOTION OF PROTUSION ALONG ICE-CONTAINED CURRENTS

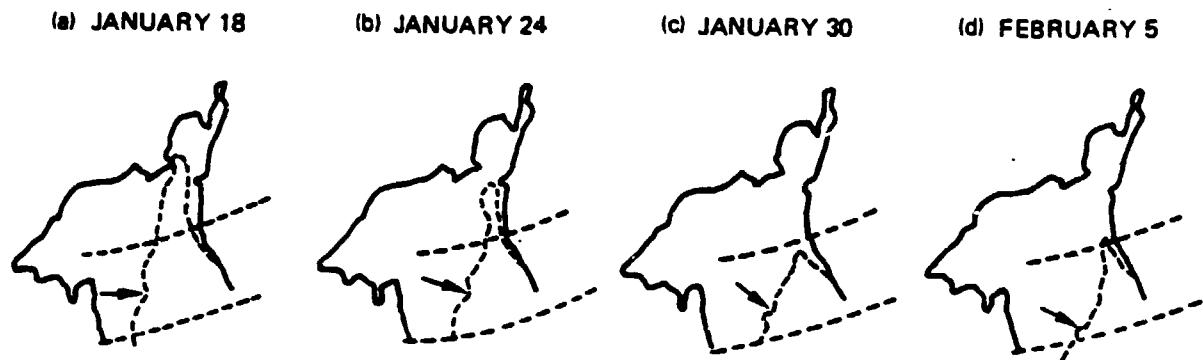


Figure 6. Movement of an ice protrusion between
18 January 1973 and 5 February 1973.

While local anomalies are frequent and the ESMR 3-day images are not most suitable for drift studies, the overall indication is that the large-scale drift does follow the persistent Okhotsk-Kuril current system.

IV. PATTERNS OF ICE GROWTH AND ACCRETION

One common process of ice accumulation and concentration is build-up about a protrusion into a flow or current. If a protrusion into an ice-bearing current exists, then it is likely to capture passing ice and concentrate it. This is natural in the case of a land protrusion since the land firmly blocks further motion in the landward direction. However, that it also happens in the case of an ice protrusion is clear from the ESMR images. Figure 7 reveals an ice protrusion in the northwest portion of the Sea on 2 January 1975 and a following build up of ice

---- JANUARY 2

— JANUARY 8



Figure 7. Accumulation of ice about a protrusion,
2 January 1975 - 8 January 1975.

concentration through 8 January. The dominant currents likely contain low-concentration ice formed along the Kamchatka Peninsula and it is this ice being blocked and concentrated by the protrusion. The edge of the protrusion facing the flow gathers ice, while at the same time the protrusion has the effect of dampening surface motion in the downflow direction--much as it contains the current in Figure 6,--promoting crystallization in these waters. In the example shown, this means that ice is captured to the north of the protrusion and formed to the south. Thus the ice concentrations on the whole are much greater in the northwest Okhotsk than in the east. Though not shown, this is confirmed by the ESMR images.

When combined with the known tendency of ice to crystallize around existing ice structures, an important conclusion may be drawn: any

— JANUARY 8
--- JANUARY 11



Figure 8. Breakdown of ice protrusion structure,
8 January 1975 - 11 January 1975.

protrusion of concentrated ice in an ice-bearing current will, in the absence of high countering stresses, quickly increase on both sides to form a much larger area of concentration. The example above clearly bears this out.

It is worth observing that high countering stresses as mentioned above do exist: Figure 8 shows a large breakdown of the described protrusion. The likely cause of this reversal is a series of atmospheric or oceanic disturbances, possibly involving a strong current induced by atmospheric forcing.

The process of accretion about an ice protrusion suggests a second, more general result: if, lacking high stresses, any protrusion will collect and concentrate ice, it follows that the only stable (nonexpanding) large-scale ice configurations are ones with minor protrusions or none

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Figure 9. Rectangular ice structure, 3 February 1974.

at all, or ones in which stresses counter friction and other accumulatory forces. In the Sea of Okhotsk, one fairly stable configuration developing frequently is the rectangular ice pattern in Figure 9. This large-scale ice pattern, or macrostructure, approximates the 100 m depth contour on the 3 February date shown. Accumulation onto this structure tends to proceed in a parallel, rectangular way, lagging in the eastern Sea where the strong Pacific inflow prevents substantial accumulation. The rectangular macrostructure occurs in many of the midwinter ESMR images; but this formation too is unstable, due to continual ice formation and perhaps to the influence of smaller protrusions. As a result, ice expands to cover most of the Sea by late March. However, it is not uncommon in the meantime for the rectangular macrostructure to distort as the ice edge advances,

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Figure 10. Two-lobed distortion
of the rectangular ice structure,
4 February 1975.

Figure 11. Wedge structure,
18 January 1973.

in particular creating two open-water lobes over the Derugin and Tinro Basins (Figure 10).

A second common macrostructure--a wedge pattern--is likely to occur late in the season, when most of the Sea is ice-covered but the Pacific inflow is restricting ice accumulation along the Kamchatka Peninsula (Figure 11). The position of the wedge correlates somewhat with the local bathymetry (Figure 3), in particular, the northern extremity of the wedge is often situated over the Tinro Basin. This suggests that convective depth could be a major factor in maintaining the wedge pattern.

V. SUMMARY AND CONCLUSIONS

It has been shown that oceanographic factors in the Sea of Okhotsk can account for many of the observed patterns of ice growth and extent. Ice forms first in shallow, protected areas of cold, low-salinity waters--specifically, in the region north of Sakhalin Island, in the Penzhinskaya Guba, and in the Tauyskaya Guba. As the early winter season proceeds, ice forms all along the northern coast and along much of the Sakhalin Island coast. Once formed, ice seems to drift in a direction approximating the Okhotsk-Kuril current system, and it accumulates about protrusions of land and then of concentrated ice. Heavy ice concentration may also contain or divert the surface currents much as the coastline does.

Because of the tendency for ice accumulation around protrusions, ice patterns cease expanding only when smooth boundaries develop, or when strong forces counter ice expansion. In the former case, in view of the drift patterns and the bottom topography of the Sea of Okhotsk, only a small number of stable ice macrostructures exist. Two macrostructures which on occasion persist for significant periods were identified as a rectangular structure and a wedge structure. These macrostructures (and in particular a 2-lobed modification of the rectangular structure) are strongly correlated with the bathymetry of the region and with the known current system, suggesting that circulation stress and convective depth play an important role in determining ice patterns.

The reader is referred to Campbell et al. (1981) for information on the significant interannual variations in the ice cover of the Okhotsk Sea and on the somewhat out-of-phase relationship of the Okhotsk ice

cover and that of the Bering Sea. The Campbell et al. study is based on ESMR satellite data for the 4 years 1973-1976. The basic patterns presented above for the Okhotsk Sea can be identified in all 4 years; but the timings vary considerably and will probably not be fully understood until additional atmospheric and oceanographic data are collected and analyzed in the context of the ice cover.

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